METHOD OF CALIBRATING A SCANNING SYSTEM.

The present invention relates to a method of
calibrating a scanning system. A scanning system in
5 this specification should be understood to mean a
combination of a machine and a probe which together are
capable of use in scanning an object in order to obtain
information about its size, shape or surface contours.

10 The machine may be, for example, a co-ordinate
measuring machine (CMM), machine tool or robot etc, and
the probe is a measuring probe with a workpiece-
contacting stylus. One type of machine has measuring
devices for measuring the movement of the machine parts
15 in three nominally orthogonal directions (referred to
as X,Y and Z axes), and one type of probe includes
measuring transducers for producing outputs indicative
of the displacement of the tip of the stylus relative
to the probe in three nominally orthogonal directions
20 (referred to as the a,b, and c axes). Although the
term 'analogue probe' is used, the outputs for the a,b
and c axes may be either analogue or digital.

In known systems, measurement errors are caused by
25 unwanted deflections of the probe, machine structure
and workpiece. Errors due to bending of the probe
stylus are the same throughout the machine volume and
may be compensated for by probe calibration. Errors
due to deflections in the machine structure may be
30 caused, for example, by the machine quill bending and
the machine bridge twisting and vary throughout the
machine volume. These errors increase, for example,
with increasing cantilevers. Errors in the object to
be measured may be caused by object deflection during

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measurement as a result of force by the probe.

Parts of the working volume of the machine may be
calibrated for measurement errors by using a
5   calibration artefact such as a calibration sphere.
However usually the calibration artefact cannot be
located at the same position in the machine's working
volume as the part to be measured and is instead
located to one side. The measurement errors determined
10   at the calibration artefact will thus be different to
those on the part.

Methods of correcting machines for acceleration induced
errors are known. One example of such a method is
15   described in European Patent No. 318557. In this
method a first article from a batch of nominally
identical articles is measured at a relatively slow
speed, noting the measurements of the positions of a
number of datum points on the article. The measurement
20   operation is repeated at a relatively fast speed noting
the measurements of the positions of the same datum
points. Any difference in the measurements are noted
as errors in a correction table.

25   Thereafter all of the articles are measured at the
relatively fast speed taking measurements of the
positions of corresponding points on each article, and
these measurements are corrected for machine
accelerations using the previously noted errors.
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Another method of correcting errors is disclosed in
WO00/62015. In this method a stylus of a probe mounted
on a coordinate measuring machine is driven into
contact with a surface of an object in a direction

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normal to its surface until a predetermined stylus
deflection has been reached. The machine is then
reversed whilst simultaneously recording the outputs of
the machine measuring devices and measuring transducers
5   of the probe. This process is repeated for a selection
of datum points around the surface of the object. The
measurements for each datum points are extrapolated to
determine the measurement which would have been taken
when the probe deflection is zero. This extrapolated
10   value relates to when the probe is just in contact with
the surface.

The object is then scanned at a slow speed and
predetermined stylus deflection. The difference at the
15   datum points between the initial measurements and the
scan is recorded.

The scans are repeated at the same stylus deflection at
greater speeds until the variation in the recorded
20   differences between the fast scan and the initial
measurements and the slow scan and the initial
measurements exceeds a defined tolerance. The last
speed which falls within this tolerance is the maximum
scanning speed. A map of the positional errors at the
25   datum points is stored along with the data relating to
the scanning speed, particular artefact, particular CMM
and probe and stylus configuration etc. It is possible
to interpolate from this map to obtain radial errors at
angles in between the radial directions at which actual
30   data was obtained (i.e. the datum points).

This method has the disadvantage that the step of
collecting the datum points is time consuming.

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The present invention provides a method of measuring an object on a coordinate positioning apparatus, comprising the following steps, in any suitable order:

  placing a first object on a coordinate positioning
5 apparatus;

  measuring said first object with a workpiece contacting probe to create measurement data of the first object, the measurement data being collected at multiple stylus deflections or probe forces;

10 for a plurality of points on the surface of said first object, extrapolating the measurement data to that corresponding to zero stylus deflection or zero probe force;

  creating an error function or map from said
15 measurement data and the extrapolated data;

  measuring subsequent objects at a known stylus deflection or known probe force;

  and using the error function or map to apply an error correction to the measurements of said subsequent
20 objects.

The term measuring includes taking measurements using either a scanning probe or a touch trigger probe.

25 The known stylus deflection or probe force may be a known constant deflection or force or a known varying deflection or force.

Preferably the step of measuring the first object with
30 a workpiece contacting probe comprises scanning the first object.

The first object may be a part in a series of substantially identical parts or an artefact with

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features approximating those of a series of parts to be
measured.

Preferably the first object is measured for each
5   measurement run at a slow speed. The error map is thus
a measure of measurement force errors.

In a first embodiment, the first object is measured at
a slow speed, and further comprises the additional
10   steps of:
        measuring said first object with a workpiece
contacting probe at a fast speed to create measurement
data of the first object, the probe having a known
stylus deflection or known probe force;
15   comparing the extrapolated measurement data
corresponding to zero stylus deflection or zero probe
force at the slow speed with the measurement data at
the fast speed;
        wherein the error function or map created from the
20   measurement data relates to the measurement data at the
fast speed;
        and wherein the subsequent objects are measured at
a known stylus deflection or known probe force at the
fast speed.
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In a second embodiment, the first object is measured at
a fast speed and further comprises the additional steps
of:
        creating a first error function or map from the
30   difference between the measurement data at a
predetermined stylus deflection or probe force at said
fast speed and the extrapolated to zero data at the
fast speed;
        measuring said first object with a workpiece

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contacting probe at a slow speed to create measurement
data of the first object;

applying the first error function or map to the
measurement data created during the slow measurement
5   run using said predetermined stylus deflection or known
probe force;

wherein said error function or map comprises a
second error function or map relating to the difference
between the measurement data obtained during the fast
10   measurement at said predetermined known stylus
deflection or known probe force and the measurement
data corresponding to zero stylus deflection or zero
probe force at said slow speed;

and wherein the subsequent objects are measured at
15   a known stylus deflection or known probe force at the
fast speed.

A second aspect of the invention provides a method of
measuring an object on a coordinate positioning
20   apparatus, comprising the steps of:

placing a first object on a coordinate positioning
apparatus;

measuring said first object with a workpiece
contacting probe at a slow speed to create measurement
25   data of the first object, the measurement data being
collected at multiple stylus deflections or probe
forces;

for a plurality of points on the surface of said
first object, extrapolating the measurement data to
30   that corresponding to zero stylus deflection or zero
probe force at said slow speed;

measuring said first object with a workpiece
contacting probe at a fast speed to create measurement
data of the first object, the probe having a known

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stylus deflection or known probe force;

comparing the extrapolated measurement data corresponding to zero stylus deflection or zero probe force at a slow speed with the measurement data at a
5   fast speed;

creating an error function or map from the comparison of measurement data;

measuring subsequent objects at a known stylus deflection or known probe force at the fast speed;
10   and using the error function or map to apply an error correction to the measurements of said subsequent objects.

The error function or map corresponds to both
15   measurement force errors and dynamic errors caused by the probe moving at fast speed.

A third aspect of the invention provides a method of measuring an object on a coordinate positioning
20   apparatus comprising in any suitable order, the steps of:

(a)   placing a first object on a coordinate positioning apparatus;

(b)   measuring said first object for a measurement run
25   with a workpiece contacting probe at a fast speed
            to create measurement data of the first object,
            the measurement data being collected at multiple
            stylus deflections or probe forces;

(c)   for a plurality of points on the surface of said
30   first object, extrapolating the measurement data
            from step (b) to that corresponding to zero stylus
            deflection or zero probe force at the fast speed;

(d)   creating a first error function or map for the
            relationship between measurement force error and

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stylus deflection or probe force from the
measurement data obtained in step (b) and the
extrapolated to zero data at said fast speed in
step (c);

5   (e)   measuring said first object with a workpiece
contacting probe at a slow speed to create
measurement data of the first object, the probe
having a known stylus deflection or known probe
force;

10   (f)   applying the first error function or map of step
(d) to the measurement data created during the
measurement run in step (e) and thereby
determining the measurement data of the first
object corresponding to zero stylus deflection or
15   zero probe force at the slow speed;

(g)   creating a second error function or map relating
to the relationship between the measurement data
obtained at a fast speed for a known stylus
deflection or probe force and the measurement data
20   corresponding to zero stylus deflection or zero
probe force at said slow speed determined in step
(f);

(h)   measuring subsequent objects at a known stylus
deflection or known probe force and fast speed;
25   and

(i)   using the second error function or map created in
step (g) to apply an error correction to the
measurements obtained in step (h).

30   The error function or map corresponds to both
measurement force errors and dynamic errors caused by
the probe moving at fast speed.

A fourth aspect of the present invention provides a

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method of measuring an object on a coordinate
positioning apparatus, comprising the steps of:

placing a first object on a coordinate positioning
apparatus;

5   measuring said first object with a workpiece
contacting probe to create measurement data of the
first object, the measurement data being collected at
multiple probe forces;

for a plurality of points on the surface of said
10   first object, extrapolating the measurement data to
that corresponding to zero probe force;

creating an error function or map;

measuring subsequent objects at a known probe
force;

15   and using the error map to apply an error
correction to the measurements of the subsequent
objects.

In each of the preceding aspects of the invention, the
20   first object may comprise an artefact having features
of known form corresponding to features on the
subsequent objects, wherein the method includes the
step of comparing the extrapolated to zero data of said
first object with its known form and thereby creating a
25   function or map of the geometric errors of the machine
and probe.

Preferred embodiments of the invention will now be
described with reference to the accompanying drawings
30   in which:

Fig 1 is a schematic diagram of an analogue probe
mounted on a coordinate measuring machine;

Fig 2 is a schematic representation of several
different constant stylus deflection scans around an

object;

Fig 3 is a graph illustrating probe deflection against object diameter;

Fig 4 is a graph illustrating probe force against
5   probe deflection;

Fig 5 is a graph illustrating the radial error against probe deflection

Fig 6 is a schematic illustration of the static correction vectors;

10   Fig 7 is a schematic representation of several different constant force scans around an object;

Figs 8-10 are schematic illustrations of a feature being deflected under measurement force;

Fig 11 illustrates the real diameter and the
15   measured diameter of a feature having low stiffness;

Fig 12 is a schematic illustration of the dynamic correction vectors;

Fig 13 illustrates the scan profiles during the method of a second embodiment of the invention;

20   Fig 14 shows a portion of the scan profiles of Fig 13;

Fig 15 illustrates a workpiece being measured according to a third embodiment of the invention;

Fig 16 is a schematic representation of a scan
25   with a sinusoidally varying stylus deflection around an object;

Fig 17 is a schematic representation of a scan with a single sinusoidally varying stylus deflection around an object; and

30   Fig 18 illustrates a section of the scan profile of Fig 17.

In a first step of the invention, a measurement force error map is generated for an object. This is achieved

by mounting an analogue probe 10 on the quill 12 of a
coordinate measuring machine (CMM) (not shown) as
illustrated in Fig 1. The analogue probe 10 has a
deflectable stylus 14 with a workpiece contacting tip

5   16. The object 18 to be measured is mounted on the CMM
machine table 20 and the probe 10 is driven slowly by
the machine quill 12 in a path around the object. The
object 18 is first scanned along a path at a first
constant probe deflection, for example 300μm. The

10 object is then scanned along this path at one or more
different subsequent probe deflections. For example,
the part may be scanned a second time with a probe
deflection of 200μm and a third time with a probe
deflection of 100μm. Fig 2 shows a representation of

15 the object 18 and the measurements obtained from the
first 22, second 24 and third 26 scans around it. Each
point on the object 18 will thus have three different
measurements A,B,C, resulting from the three different
scans at different probe deflections. For each point

20 on the object, the measurements may be extrapolated
back to calculate the measurement which would have been
taken if the probe deflection was zero. Fig 3 shows a
graph of the probe deflection against object diameter.
The actual object diameter is shown at zero probe

25 deflection. The step of extrapolating to zero probe
deflection allows the measurements at zero probe
deflection to be determined without the errors of
actual measurement, caused by probing force errors. A
passive probe is suitable for use in this method, such

30 a probe may comprise a stylus deflectable against
springs.

This information enables a measurement force error map
of the part to be produced. If the scans of the part

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were taken at a slow speed, this results in negligible
dynamic errors due to very low accelerations of the
probe and machine.

5   Fig 4 shows the relationship of probe force against
probe deflection. The probe acts within Hook's law
such that when there is zero probe force, there is zero
probe deflection.

10 Fig 5 illustrates the relationship of radial error
against probe deflection. Points A,B and C relate to
the radial error at probe deflection 100µm, 200µm and
300µm respectively. By using these points to
extrapolate to zero probe deflection, zero radial error
15 is achieved. Once the function relating probe
deflection and radial error has been determined, a
subsequent measurement taken at any probe deflection,
for example point P, may be corrected to zero radial
error using this function. As there is a linear
20 relationship between probe deflection and radial error,
the function for correcting measurements at a given
probe deflection is also linear.

Alternatively the measurement force error may be in the
25 form of an error map. This could be in the form of a
look-up table, with different error corrections for
different stylus deflections. The error map could be
in the form of a polynomial function.

30 Fig 6 shows the error corrections for points on the
scan. Each point on the scan has a different radial
correction 38 which is applied for a certain stylus
deflection. If a subsequent object is scanned at a
stylus deflection of 300µm 36, the measurement force

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error function or map may be used to correct the
measured dimensions 36 taken at this stylus deflection
to the actual part dimensions 34 corresponding to the
part being scanned at a deflection of 0µm.

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This method is not limited to each scan having a
constant deflection, as long as points on the object
surface have measurement data corresponding to
different stylus deflections to enable the measurement
10   data to be extrapolated to zero. For example, Fig 16
illustrates a first scan profile 60 around an object 18
taken at constant deflection and a second scan profile
62 taken using a sinusoidally varying deflection.
Points P1,P2,P3 on the object surface thus each have
15   two measurements taken at different probe deflections.
This measurement data may be extrapolated to zero as
previously described.

It is also possible to collect sufficient measurement
20   data during a single varying scan profile. Fig 17
illustrates a single scan profile 70 around an object
18, the scan profile 70 being taken using a
sinusoidally varying stylus deflection. Fig 18
illustrates a section of the scan profile 70. Over a
25   small angle 72, scan profile 70 contains many data
points taken at different stylus deflections. Assuming
changes in the surface are small over angle 72 (eg part
deflection and uniformity of surface), these data
points taken at different stylus deflections over angle
30   72 may be used for the extrapolation to zero
calculation. This is also possible if there is a
change in the surface profile over angle 72, as long as
the change can be assumed to be linear.

Alternatively, instead of scanning the object several
times at different probe deflections, it may be scanned
several times with the probe having a different
constant force for each scan. For example, the object
5   may be first scanned with a constant force between the
stylus and the object of 0.3N. The object may then be
scanned a second time with a constant force of 0.2N and
a third time with a constant force of 0.1N. Each of
these scans may have the same or different stylus
10   deflections. Fig 7 shows a representation of the
object 18 with an actual part dimension 34 and the
measured dimensions obtained from the first 28, second
30 and third 32 scans at different constant probe
forces.
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As before, for a point on the surface of the object,
there are three sets of data relating to the scans at
different probe forces. This data may be extrapolated
back to enable the point which would be measured with
20   zero force between the stylus and workpiece (i.e. the
actual part dimensions) to be determined. As described
previously, an error function or map may be created
relating measurements taken at a given probe force to
the correct measurements for a given point determined
25   for zero probe force by the extrapolating to zero
technique. Subsequent measurements at a given probe
force may be corrected for measurement force errors
using this measurement error function or map.

30   As with the previous method, sufficient data may be
collected from a single scan of varying probe force (eg
having a sinusoidal profile) to do the extrapolate to
zero calculation.

This method is suitable for use in an active scanning probe, in which a motorised mechanism is used to control and modulate the contact force with the component to be measured.

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The object may comprise a part of a series of parts to be measured. In this case a measurement force error map of this part is produced by this method. Alternatively, the object may comprise an artefact having features corresponding to the features on the parts to be subsequently measured. These features may be, for example, spheres, ring gauges, plug gauges etc. Use of the artefact allows geometric errors in addition to the probing force measurement errors, to be determined. Geometric errors are errors of the machine and probe, for example non-linearity of the machine scales or the machine axes not being straight. As the forms of the features on the artefact are known, they may be used to correct for geometric errors of the machine and probe. This may be done by comparing the extrapolated to zero data of the artefact with the known form of the artefact and producing a geometric error map to correct subsequent parts with.

This method has the advantage that the errors due to probing force measurement errors and geometric errors can be separated. This would not be the case if, for example, measurement data from a scan with 300μm deflection is compared with the known form of the artefact. In this case the probing force measurement error and geometric error would be combined into one correction and it would not be possible to separate them.

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This method of correcting for separate measurement
force errors and geometric errors has the advantage
that it takes into account the errors due to deflection
of the object being measured. Objects with low
5   stiffness and/or thin walls may deflect with the
probing force whilst being measured.

Fig 8 illustrates a feature 50 to be measured which has
low stiffness. When the feature is contacted with a
10   probe 10, as shown in Figs 9 and 10, the feature
deflects away from the probe. This deflection of the
feature caused its diameter measured at force F to
appear smaller than its actual diameter. Fig 11
illustrates the actual diameter 52 of the feature and
15   the measured diameter 54 using a probe force F.
Similarly, the inner diameter of a ring would appear
larger than its actual diameter for the same reason.
At zero probe deflection or zero probe force there will
be zero deflection of the feature. Thus the
20   measurement force error function or map created by the
method of this invention takes account of these errors
by this extrapolating to zero step.

In a second step of the invention, the dynamic errors
25   of the system are determined. Dynamic errors may be
caused, for example, by machine bending due to
acceleration. Once the measurement force error function
or map has been produced as described above, the object
is scanned at a high speed. The high speed scan is
30   carried out at either constant probe deflection or
constant force, as above. In addition, the high speed
scan is preferably performed at a constant speed. The
measurement data from this fast scan is compared with
the measurement force error corrected slow scan

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relating to the actual dimensions of the object,
produced as described in the first step of the
invention. A dynamic error function or map may be
produced by comparing the fast scan and the measurement
5   error corrected slow scan. This dynamic error map is
used to correct subsequent scans taken at a fast speed.

The subsequent scans do not need to have the same
stylus deflection or probe force as the original fast
10   scans as the dynamic error function relates the error
to the deflection or force. However it is desirable to
use a similar fast speed for the subsequent scans.

Fig 12 illustrates the measurements taken during the
15   fast scan 40 and the actual dimension 42 of the object
created by measurement force error correcting the slow
scan as previously described.

The dynamic error map has been combined with the
20   measurement force error map or function to create a
total feature map. This is done by adding the
measurement force error correction vectors 38 around
the part illustrated in Fig 6 with the dynamic error
correction vectors around the part to create combined
25   correction vectors 44 illustrated in Fig 12.

This method has the advantage that as the measurement
errors are determined by scanning the object at
different probe deflections or different forces, the
30   measurement errors are known for every point on the
surface of the object. Thus no interpolation is
required.

In a second embodiment of the invention, the

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measurement force errors and the dynamic errors may be
determined in combination. Such a method will now be
described with reference to Figs 13 and 14.

5   In a first step, an object is scanned at a slow speed
for example 10mm/s with a first deflection, for example
200μm. Fig 13 shows the profile of the slow scan S1.
The object is then scanned along the same path at a
fast speed, for example 100mm/s and at a second
10   deflection, for example 100μm. Fig 13 shows the
profile of the fast scan F1. The object is then
scanned along the same path at the fast speed 100mm/s
and at the first deflection 200μm. Fig 13 shows the
profile of the fast scan F2.
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Fig 14 shows a portion of the S1,F1 and F2 scan
profiles around the object. F1 and F2 are profiles for
scans of the same fast speed (100mm/s) but different
deflections (100μm and 200μm respectively). By
20   extrapolating to zero deflection, the profile of the
object for a high speed (100mm/s) scan with zero
deflection can be determined. This profile is shown as
HSZD on Fig 14. The error due to deflection of the F2
scan may thus be determined. This deflection error is
25   shown as e_1, on Fig 14.

As scans S1 and F2 were carried out with the same probe
deflection (200μm), the deflection error e_1, may be
applied to the profile of scan S1 to find the profile
30   corresponding to a scan at low speed with zero
deflection. This profile is shown as LSZD on Fig 14
and corresponds to the surface of the object.

The LSZD is now used as a base line. The error between

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the LSZD baseline and the F2 scan is now determined. This is labelled e_2 on Fig 14. The errors e_2 may be stored as a correction map or function.

5   Subsequent objects may now be measured at a speed and deflection corresponding to scan F2 and corrected using the correction map or function.

        This method may be used with a force-measuring probe
10   rather than a deflection-measuring probe. In this case, scans S1 and F2 are carried out at a first probe force and scan F1 is carried out at a second probe force. The two fast scans must then be extrapolated to zero force to determine the high speed zero force
15   profile and thus the error due to force of the F2 scan may be determined.

        The measurements of the object during the S1, F1 and F2 scans may be determined by using either a scanning
20   probe or a touch trigger probe. A touch trigger probe may be electronically loaded so that it triggers at a certain force. Thus during the S1 and F2 scans the probe is loaded to trigger at a first force and during the F1 scan the probe is loaded to trigger at a second
25   force, enabling the two fast scans to extrapolate to zero force.

        It is not necessary for the slow scan S1 to have the same stylus deflection or probe force as the fast scan
30   F1. This is because the relationship between stylus deflection/probe force and measurement error is determined at the fast speed from scans F1 and F2, which enables comparison with any stylus deflection/probe force at the slow speed.

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A third embodiment of the invention will now be
described with reference to Fig 15. A stylus 10 of a
probe is driven into contact with a surface of an
object 18 along a path 46 in a direction normal to the
5   object's surface until a predetermined stylus force has
been reached. This step is repeated along the same
path for a plurality of different predetermined stylus
forces. The measurement data along this path is used
to extrapolate back to enable the point which would be
10   measured with zero forces between the stylus and
workpiece to be determined. This is the nominal object
measurement.

This process is repeated for a selection of datum
15   points around the surface of the object. The data from
each of these datum points is used to create an error
map as previously described to correct subsequent
measurements. Measurements of the surface of the
object between the datum points are corrected by
20   interpolating the error map between the datum points.